# Evaluation of Dredged Material Plumes—
# Physical Monitoring Techniques

**PURPOSE:** Information on the extent and nature of suspended-sediment plumes generated by dredge activities is necessary to enhance understanding of technical issues including sediment transport processes and associated environmental concerns. This technical note reviews recent suspended-sediment plume monitoring projects and evaluates various techniques used to monitor suspended-sediment plumes, including several emerging techniques. Recommendations are provided on techniques for various monitoring requirements.

**BACKGROUND:** All types of dredging create some form of sediment plume in the water column. Of particular interest are plumes associated with (a) mechanical (e.g., bucket, clamshell) and hydraulic (e.g., pipeline cutterhead, hopper) dredges, (b) overflow from hopper dredges, and (c) open-water disposal of dredged material. Sediment plumes have been hypothesized to have adverse effects on biological resources either through impact to water quality or increased siltation (Barr 1987). To gain a better understanding of the temporal and spatial dynamics of sediment plumes, one needs to monitor the plumes to determine their composition, extent, and duration. Numerous techniques have been used to monitor sediment plumes, ranging from collection of water samples using simple water samplers to highly complex systems involving state-of-the-art instrumentation. Given the variety of techniques available to monitor dredge plumes, understanding the advantages and limitations of the various techniques is important to determine which technique will provide the most cost-effective approach for particular monitoring requirements.

**INTRODUCTION:** A variety of parameters are associated with dredge plumes that can be monitored. Selection of parameters to monitor will depend on the purpose of the monitoring effort and conditions at the site. Typical monitoring programs for dredge-related sediment plumes measure one or more of the following water quality parameters associated with the plume: (a) total suspended solids, (b) turbidity, (c) density, (d) temperature, (e) conductivity or salinity, (f) pH, and (g) fluorescence.

Most dredge plume monitoring efforts focus on monitoring total suspended solids (TSS) and/or turbidity associated with the dredge plume. TSS is a measure of the total mass of material in a given volume of water and is measured in milligrams/liter (mg/L). The majority of studies conducted on the impact of sediment plumes on the environment focus on TSS. Turbidity, a measure of the light-scattering properties of a volume of water, is also related to the type and quantity of particles suspended in the water. While numerous units exist for reporting turbidity, nephelometric turbidity units are commonly used to report turbidity associated with sediment plumes. Since TSS cannot readily be measured in situ, turbidity is typically measured and used to estimate TSS using empirical calibrations relating turbidity to TSS. These calibrations are site specific and subject to significant errors. In many instances, establishing a reliable relationship between TSS and turbidity is not possible because of variation in characteristics of the suspended material.

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Nonetheless, turbidity is the parameter most commonly used to identify dredge-induced sediment plumes.

The density of a sediment plume is related to TSS. However, under most conditions, density variations are negligible except in portions of the plume with very high TSS. Additionally, density varies depending on prevailing temperature and salinity conditions. Therefore, density is seldom considered to be an important parameter for dredge plume monitoring efforts.

Conductivity is a measure of the resistance of the water to electrical flow. Conductivity measurements, in conjunction with temperature measurements, are used to calculate water salinity. Salinity measurements are useful in differentiating between water masses of different origins within the same water body. Therefore, salinity measurements can be useful in identifying sediment plumes if water associated with the plumes has salinity levels significantly different from the surrounding water.

Dissolved oxygen (DO) and pH are chemical parameters commonly measured as indicators of water quality. DO represents the concentration of oxygen dissolved in water. Decreases in DO can significantly impact biological resources. Barr (1987) reported that sediment plumes consisting of anoxic sediments may lower DO concentrations in the water column influenced by the plumes. Sediment plumes may also alter pH levels in waters associated with the plume (U.S. Environmental Protection Agency (EPA) 1976).

Fluorescence is a measure of the light emitted by a volume of water when illuminated with various types of radiant energy. Depending on the type of energy used to illuminate the sample, measurements of fluorescence can be used to monitor chlorophyll levels. Fluorescence can also be used to measure concentrations of certain dyes that can be injected into the water during the generation of the plumes. By measuring the dye concentrations, tracking the water bodies containing the sediment plumes is possible (Battelle 1991).

The objectives of measuring the various water quality parameters discussed above are usually twofold, first to determine the water quality associated with the plume and second to track the plume both in space and time. Knowledge of the spatial extent of a given plume is necessary to determine areas of potential plume impact. Similarly, knowledge of the time history of a plume provides information on how long a plume is present in a particular area and the time required for the plume to dissipate.

For some plume-monitoring projects, also important is measuring various physical parameters not directly associated with water quality such as currents, waves, and water elevations. Currents carry plumes from the area in which they were generated into adjacent waters. Therefore, data on the current structure can be used to estimate the movement and spatial extent of the plume. Waves increase turbulence in the water column that can put additional sediment into suspension and prevent material in suspension from settling out. Information on the tidal levels can be useful in determining tidal currents and water depths in the dredge and disposal areas.

**TECHNIQUES USED TO MONITOR SEDIMENT PLUMES:** As discussed above, numerous parameters can be measured to monitor dredge-induced sediment plumes. The various sampling techniques fall into four general categories:

 a. In situ sampling of water quality parameters.

 b. Acoustic monitoring.

 c. Remote sensing.

 d. Dye studies.

## In Situ Sampling of Water Quality Parameters

Sampling techniques for monitoring plumes involve placing instruments in the water column to directly measure water quality parameters or other physical parameters. In situ techniques also include collection of water samples from the water column for analysis either in the field or the laboratory. The various parameters of interest are listed below, and a brief description of the sensors used to monitor the parameters is provided. In addition, the platforms that are commonly used to deploy the instruments are discussed. A description of a recent field-monitoring effort using in situ instruments is also provided.

## Instruments for Measuring Parameters In Situ

**Total suspended solids:** Historically, TSS has been measured by collecting water samples and analyzing these samples in an offsite laboratory. Water samples can be collected using a bottle sampler or a submerged pump. Independent of the collection method, care must be taken to ensure that suspended particulate matter does not settle out of suspension or flocculate during collection or prior to analysis. Offsite laboratory analysis is time-consuming, expensive, and cannot provide data in the short term. However, this approach is considered to be the most accurate and reliable method for measuring TSS. The only alternative has been to estimate TSS based on other measurements such as turbidity or acoustic backscatter, both of which have limitations as discussed below.

Recently, instrumentation has been developed that provides an alternative for measuring TSS in situ more accurately than can be achieved using correlation with turbidity. Laser In Situ Scattering and Transmissometry (LISST) measures the scattering of a laser beam by particles in a volume of water. The LISST-25 is a small, self-contained unit suitable for field deployment with real-time data return capabilities (Sequoia Scientific, Inc. 1998). The instrument is capable of measuring particle total volume, particle total area, and Sauter mean diameter within a particle range of 1.2 to 250 μm. These parameters are defined as follows:

 a. Particle total volume is the volume of material per volume of water.

 b. Particle total area is the projected cross-sectional area of the particles per volume of water.

 c. Sauter mean diameter is the ratio of the particle total volume to the particle total area.

If the density of the suspended particulate matter is assumed, calculating TSS by multiplying the particle total volume by the assumed density is possible. Other models in the product line of the LISST instrument are also capable of measuring the particle size distribution.

LISST instruments have not been used extensively in field studies of plumes, and little documented information on their performance exists. A recent study comparing the LISST to traditional methods of measuring suspended-sediment concentration found the LISST provided accurate measurements of total volume concentration of suspended sediments (Traykovski, in preparation). Once the accuracy and limitations of these systems have been thoroughly documented, this instrument could prove very useful for in situ monitoring of sediment plumes.

**Turbidity:** Turbidity is the apparent "cloudiness" of water produced as light is scattered by particulate matter or dissolved material in the water (D&A Instruments 1989). Turbidity can be measured in situ using either a transmissometer or a nephelometer. A transmissometer projects a narrow beam of light through a volume of water and measures the intensity of the beam as it exits the volume of water. If particles are in the water, they will attenuate the beam of light such that the light exiting the volume is less than the light entering the volume of water. The amount of attenuation can be measured, and with the appropriate calibration, these measurements can be used to estimate suspended-particle concentrations using empirically derived calibration curves. At low particle concentrations, transmissometers are very sensitive to small changes in particle concentration and/or size; however, at high-particle concentrations, transmissometers become saturated and lose their sensitivity to variations in concentration (D&A Instruments 1989). Therefore, while transmissometers are very useful at measuring low-particle concentrations, they are inadequate for measurements at TSS levels above approximately 150 mg/L (Zaneveld, Spinrad, and Bartz 1979).

Nephelometers project a beam of light into a volume of water and measure the amount of light scattered out of the beam. The amount of light scattered is almost entirely dependent on the amount and size of particulate matter present in the volume of water. Ideally, a nephelometer would measure the amount of light scattered at all angles. Such a nephelometer is impractical, however, and standard nephelometers measure the scattered light at only one angle (D&A Instruments 1989). Nephelometers used for in situ measurements are, in general, referred to as optical backscatter sensors (OBSs). OBSs measure the amount of infrared light backscattered from a volume of water. While suspended sediment will reflect infraenergy, organic matter will not (Tubman 1995). This characteristic of OBSs makes them well suited for measurement of sediment plumes because it does not bias the data by including organic matter. Since the OBS is measuring backscatter, its design is simple and compact relative to that of a transmissometer. More importantly, the OBS is capable of measuring much higher particle concentrations than a transmissometer, though it lacks the accuracy of the transmissometer at low-particle concentrations (D&A Instruments 1989). Like the transmissometer, particle concentrations in the water can be estimated from OBS measurements using empirically determined calibration curves.

One of the main benefits of measuring turbidity is that turbidity sensors are relatively simple, inexpensive, and robust. The objective of most turbidity measurements is to identify the presence of suspended solids and quantify the TSS based on a correlation between turbidity and TSS. If making direct measurements of TSS in situ were possible, significantly less interest in measurements of turbidity would exist. However, in the absence of a reliable means to measure TSS in situ,

the standard practice has been to use turbidity measurements to estimate TSS. Such estimates are accurate only under the following conditions (D&A Instruments 1989):

a. All measurements being compared are made with the same turbidity sensor.

b. The turbidity sensor is calibrated with a reference standard and suspended material from the area where the measurements are being taken.

c. Particle size and composition of the suspended material do not change significantly during the measurement period.

Turbidity can also be measured in the field by collecting water samples and using portable instruments to analyze the samples. While these instruments are typically less expensive than in situ sensors, the measurements take longer and may not represent true in situ conditions since particles may settle out of suspension prior to analysis.

**Conductivity, temperature, and pressure:** Conductivity, temperature, and pressure (depth) are standard hydrographic measurements taken by an instrument referred to as a CTD. The basic technology for making these measurements has proven to be highly accurate. Conductivity, temperature, and pressure are used with well-established relationships to determine other parameters including salinity, density, and water depth.

**Density:** Density is calculated from measurements of temperature, salinity, and pressure.

**Salinity:** Salinity is calculated from measurements of conductivity and temperature.

**Dissolved oxygen:** Sensors for measuring dissolved-oxygen concentration in situ have evolved significantly in recent years. Modern sensors are compact, reliable, and highly accurate.

**Fluorescence:** Fluorescence is measured by illuminating a volume of water with a light source of known wavelength and measuring the amount of energy emitted from the volume at another known wavelength (Battoe 1985). Depending on the wavelength used to illuminate the sample, fluorescence can be used to measure the presence of chlorophyll, petroleum hydrocarbons, and special dye tracers. Until recently, fluorescence was measured in the field by taking a water sample and running it through a field instrument. However, fluorometers can now measure fluorescence in situ.

**Currents:** Instruments capable of measuring currents in situ include mechanical, electromagnetic, and acoustic Doppler sensors. Historically, the most commonly used type of current sensors have been the mechanical and electromagnetic sensors. Mechanical sensors measure currents using a propeller or the deflection of a foil suspended in the water. Electromagnetic sensors measure electric fields generated by currents passing by electrical sensors. Both mechanical and electromagnetic sensors can be difficult to deploy and are susceptible to fouling. These sensors are limited to measuring water velocity in the waters surrounding the sensor at a fixed point in the water column.

Acoustic Doppler current sensors are now widely used to measure current velocity profiles under a variety of conditions. The Broadband™ acoustic doppler current profiler (ADCP) manufactured

by RDInstruments has been one of the most widely used acoustic Doppler sensors, though similar instruments are now being sold commercially by other manufacturers. Acoustic Doppler sensors project beams of acoustic energy into the water column and measure the Doppler shift in the signal reflected from particles suspended in the water column. The Doppler shift is directly related to the velocity at which the particles are moving. By projecting the beams in different directions, the instruments can resolve the various velocity components of the water in which the particles are suspended. Acoustic Doppler current sensors can continuously measure velocities at discrete intervals over almost the entire depth of the water column. The system can either be mounted on a fixed platform providing long-term current data at one location or mounted on a roving vessel making measuring currents throughout a given region possible. Acoustic Doppler current sensors can provide highly accurate and reliable current measurements.

**Water levels:** There are numerous commercially available sensors for measuring water elevations. Sensors can be either bottom mounted in remote locations or mounted to piers or other permanent structures.

**Waves:** A number of instruments are available for measuring wave parameters, with bottom-mounted pressure sensors being the standard in shallow coastal waters. Pressure sensors measure the variation in water pressure resulting from the increase in water height as the wave passes over the sensor. In water depths less than 50 ft, pressure-sensor type instruments have proven to be highly accurate and increasingly more reliable. Internal recording and real-time instruments are available.

Instruments capable of measuring not only the wave height but also the wave direction are available. While these instruments and the accompanying data processing are significantly more complex than simple wave height sensor, their data can be extremely useful in situations where the direction of wave approach is important.

### Instrument Platforms for Measuring In Situ Water Quality Parameters

The platform used for deploying instruments to collect in situ water quality parameters is dependent on the requirements for the monitoring program. Typical deployment platforms include fixed platforms, vessels, or towed vertical profilers.

**Fixed platforms:** Fixed platforms are used to deploy instruments when a continuous time series of measurements are required at a specific location for extended periods of time. The platform is typically bottom mounted, and the instruments are attached to the platform. Sensors for measuring water quality parameters are usually mounted at least 1 m off the bottom so that the sensors will be above the bottom boundary layer. Instruments can also be placed on pier pilings or other fixed structures in an appropriate location. The instruments are battery powered, record data internally, and are periodically retrieved for data downloading. Alternatively, the instruments can be cabled to shore for real-time data collection.

**Sampling from a vessel:** If measurements are required at numerous locations over short periods of time, the standard procedure is to lower the instruments from the side of a vessel to the desired water depth. If multiple instruments are being used, the instruments can be mounted on a common

frame for deployment. This reduces sampling time and provides synoptic measurements of the parameters being measured.

Many instruments are also capable of providing continuous data outputs, making it possible to profile the water column by slowly lowering the instruments from the surface of the water to the bottom. Profiles can provide valuable information on the vertical structure of the water column; however, sampling time can be significantly increased depending on the water depth and the rate at which profiles can be conducted.

**Towed vertical profiler:** Several platforms have been developed in recent years that undulate through the water column from near the surface to near the bottom while being towed behind a vessel. Numerous instruments can be mounted on the platforms and connected to shipboard data collection systems for data logging and real-time display. With such systems, rapidly collecting information on the vertical structure of the water column over large areas is possible. Water pumps can also be mounted on these platforms with hoses connected to the ship, making collecting water samples "on-the-fly" possible concurrently with the other parameters being measured. While these systems have been used extensively in open-water studies, few applications have been made in estuaries and navigation channels where typical water depths are less than 45 ft. Rapid variations in water depths in most estuarine environments may limit the ability of such systems to provide complete profiles of the water column. Towed platforms have the inherent capability to provide far greater spatial coverage of the water column both horizontally and vertically than traditional stationary-profiling platforms.

## Examples of Monitoring Studies Using In Situ Techniques

Monitoring conducted as part of the Boston Harbor Navigation Project is an excellent example of the use of in situ instrumentation to identify and track sediment plumes (Nilson, Hadden, and Giard 1998). Regulatory agencies required that sediment plumes created by the dredging and disposal of dredged material be monitored to determine compliance with applicable water quality standards. Monitoring involved the measurement of turbidity, temperature, DO, pH, conductivity, and salinity at various locations near the dredge and disposal areas using a YSI multiparameter instrument. The YSI 6000 is one of several systems capable of measuring a variety of parameters using a single, compact instrument package suitable for deployment from a small workboat and can be lowered through the water column to provide vertical profiles of water quality parameters. During this project, the instrument package was lowered to a given depth and slowly "towed" through the sediment plumes to locate the densest portion of the plume. Once the densest portion of the plume was identified, a submersible pump was used to collect water samples from middepth and near-bottom waters. The water samples were analyzed in the laboratory for TSS and a variety of chemical parameters. In addition, an electromagnetic current meter was deployed to measure near-bottom current speeds and directions.

Differential Global Positioning System technology, interfaced with navigational software on a PC, allowed for accurate location of the water quality samples relative to the dredging and disposal sites. The monitoring project was successfully able to demonstrate to the regulatory agencies that dredging and disposal were being conducted in compliance with the required water quality standards. Based on these results, future monitoring requirements for other parts of the same project

will be reduced (Nilson, Hadden, and Giard 1998). With advances in in situ instrumentation, such monitoring efforts have been increasingly successful at identifying and tracking plumes.

## Acoustic Monitoring

Acoustic transducers project a beam of acoustic energy into the water column that is reflected and scattered by suspended particles in suspension in the water column. The acoustic energy reflected back to the transducer is referred to as backscatter, and the amount of backscatter is dependent on the size distribution of the particulate matter relative to the wavelength of the acoustic energy and the concentration of the particulate matter. This property of acoustics makes it an extremely useful tool in identifying and tracking plumes of suspended sediments. The acoustic sensors that have been used or that have the potential to be used to monitor sediment plumes include the following:

> *a.* Fathometers and related instruments.
>
> *b.* Acoustic Doppler current instruments.
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> *c.* Sidescan sonar.
>
> *d.* Scanning sonar.

**Fathometers and related instruments:** Fathometers can display backscatter from suspended solids and can provide qualitative information on the amount of suspended material in the water column. A study (Panageotou and Halka 1994) by the Maryland Geological Survey on plumes generated by open-water disposal of dredged material in Chesapeake Bay successfully used fathometers to identify and track plumes associated with the disposal of dredged material from hopper barges. During the study, the sediment plume from the discharge of a hydraulic dredge pipeline into open water and the sediment plumes created by the discharge of dredged material from hopper barges were tracked using a 200-kHz fathometer and a 300-kHz acoustic tracking system very similar to a fathometer. In addition, turbidity measurements in the plumes were collected with a transmissometer and an OBS. Turbidity measurements were related to suspended-sediment concentration using calibration curves developed for each instrument with sediments from the dredged area. Using a combination of fathometers and turbidity sensors, the study was able to effectively delineate the boundaries of the sediment plume and provide information on the concentration of suspended material in the plume.

Another study employing a similar approach was conducted on plumes generated by hopper dredges in Chesapeake Bay (Nichols, Diaz, and Schaffner 1990). Both the plumes created by overflow from the hopper dredge and from disturbance by the draghead as it moved across the bottom were monitored during this study. The study included sampling of the hopper overflow, sampling of the plume in the water column from fixed stations, and tracking the plume with a 300-kHz acoustic fathometer-type system. The acoustic system was able to identify surface plumes associated with the hopper overflow, near-bottom plumes created by the dredge drag arm, and material from the hopper overflow settling out of the water column. The acoustic system provided qualitative information on the structure and dissipation of the plume. The acoustic information was augmented by turbidity measurements taken with a transmissometer and water samples collected using a submersible pump. The water samples were analyzed in the laboratory for TSS and salinity. The

study determined that while water quality standards were exceeded in the sediment plume, impact to the environment was not detectable.

While fathometers have been demonstrated to be effective tools for mapping the dimensions of plumes, they provide little more than qualitative information on the concentration of suspended particles. In addition, the sensitivity of the fathometers to increased concentrations of suspended particles is highly dependent on the gain and power settings of the instrument.

**Acoustic Doppler sensors:** Recognizing the limitations of fathometers and similar instruments, numerous studies have attempted to measure the intensity of the backscatter with acoustic systems and use this data to estimate concentrations of suspended particles (Thevenot, Prickett, and Kraus 1992). The instrument most commonly used to measure backscatter intensity is a type of acoustic Doppler sensor identical to those used to measure water velocity. Acoustic Doppler sensors are used because they are already set up to collect and record the backscatter-intensity data. To calculate sediment concentration from backscatter intensity, these studies use empirically derived equations and acoustical theory in varying degrees. In studies heavily dependent on empirically derived equations, numerous water samples are collected concurrently with the acoustic data. Water samples are analyzed for TSS, and the results are compared with the concurrent acoustic backscatter measurements. Based on this comparison, an equation is derived that relates the TSS to the acoustic backscatter, which is then converted into TSS. The calibrations are material and site specific and assume a constant grain-size distribution. Such studies can provide reasonable results in situations where sediment grain-size distributions and sediment concentrations remain relatively constant in both time and space, such that it is possible to collect concurrent acoustic and water-sample data.

The U.S. Army Engineer Waterways Experiment Station (WES) used a similar approach as described above in a study of sediment flux in San Francisco Bay (Fagerburg and Pratt 1995). During the study, a vessel-mounted ADCP measured currents and backscatter along range lines that crossed various sections of the bay. Concurrent with the backscatter measurements, water samples were collected at different stations and at different depths along the same track lines. The water samples (over 6,000 total) were analyzed in the laboratory for TSS, and a correlation was developed between the backscatter measured with the ADCP and TSS. Using this correlation, all of the backscatter data collected along a range line were converted into TSS. Based on the estimated TSS and the measured currents, estimates of the total flux of material across each range were calculated.

Given the logistical problems associated with collection of water samples, researchers have attempted to convert backscatter directly into TSS through the use of acoustical theory. The application of acoustic theory to convert acoustic backscatter data into estimates of TSS requires that the following conditions be met (Tubman 1995):

  *a.* The particle size distribution of the suspended material is known.

  *b.* Salinity, temperature, density, and sound speed of the water are known.

  *c.* The acoustic system has been calibrated, and certain constants relative to the transmitted and received signal strength have been determined.

The calculation of sediment concentrations assumes that the acoustic energy, including the backscatter, is undergoing Rayleigh scattering. The description of the Sonar equation is taken from Clay and Medwin (1977), Ogushwitz (1994), and Tubman (1995). Under the theory of Rayleigh scattering, the volume backscattering strength, $S_V$, is defined as follows:

$$S_V = 10 \log_{10}(C_V k^4 a^3) + 10 \log_{10}(k_I) + 20.0$$

where

$\quad C_V$ = volume concentration of scatters

$\quad k$ = wave number of acoustic energy

$\quad a$ = particle radius

$\quad k_I$ = constant

Since $S_V$ is dependent on grain size, it must be calculated for each individual grain-size class. Furthermore, since $S_V$ is dependent on grain size to the third power, minor errors or changes in the grain-size distribution can significantly impact the calculation of the volume concentrations of scatters.

The volume backscattering strength, $S_V$, is related to the backscatter measured at the transducer, $RL$, by the sonar equation defined as follows:

$$RL = SL - AL + S_V - RV$$

where

$\quad RL$ = backscatter strength measured at transducer

$\quad SL$ = source level from transducer

$\quad AL$ = all acoustic losses

$\quad S_V$ = volume scattering strength

$\quad RV$ = ensonified volume

The source level, $SL$, and the backscatter strength, $RL$, are known from the data if the system and the transducer have been calibrated. The ensonified volume, $RV$, is determined from the geometry of the transducer and its calibration. The acoustic loss value, $AL$, includes several types of acoustic losses that can be calculated from acoustic theory using the measured environmental conditions including temperature, salinity, density, and sound speed. $AL$ also includes certain losses that are dependent on the concentration and particle size of the suspended material.

Therefore, in theory, all values in the sonar equation can be determined with the exception of the suspended-sediment concentration and the particle size distribution, which are part of the $S_V$ and $AL$ terms. Assuming that the particle size distribution can be determined from sediment samples collected at the site, the sonar equation can be solved for the sediment concentration.

Attempts have been made to determine TSS by applying acoustic theory to measured backscatter intensity. These studies include the measurement and characterization of mine-tailing discharges (Hay 1983), suspended-sand concentrations in the nearshore (Hanes et al. 1988), and open-water sewage plumes (Damman et al. 1991). In addition, a series of studies have been conducted by WES to measure suspended sediment associated with dredge plumes using an acoustic system. The research at WES lead to the development of the PLUmes MEasurement System (PLUMES), which consists of a Broadband™ ADCP modified to include a fifth beam that is projected straight down through the water column. The backscatter intensity is measured in discrete segments along the fifth beam. The use of a fifth beam has many advantages, including a more easily defined sample volume and simplified beam geometry. As backscatter data are collected along the fifth beam, the ADCP also measures currents using the other four beams. The current data can be used to estimate the direction and speed at which the plume is moving.

The PLUMES can be mounted either off the side of a vessel or in a tow body that is dragged behind the vessel. In a typical deployment, the vessel runs transects across the area where the sediment plumes associated with dredging activities are suspected to be and the PLUMES is used to identify and track these plumes. By running transects along predetermined grid patterns, delineating the edges of the sediment plumes and estimating the spatial extent of the plumes are possible.

The PLUMES system has undergone laboratory testing and several field tests, including deployments in Mobile Bay, Alabama, Tylers Beach, Virginia, and a deepwater disposal site offshore of San Francisco, California. The laboratory testing of the prototype system was successful for glass beads and sand particles from 38-850 μm at concentrations from 5 mg/L to 1,000 mg/L (Lohrmann and Huhta 1994). The testing showed that Rayleigh scattering accounted for the observed backscatter for the given particle sizes and concentrations. However, the laboratory tests were unsuccessful for particle sizes less than 10 μm (Lohrmann and Huhta 1994).

Ogushwitz's (1994) analysis of field data collected using a prototype of PLUMES in Mobile Bay, Alabama, confirmed that under field conditions, the observed scattering is consistent with Rayleigh scattering theory. The analyses also found that acoustic losses from attenuation, which are included in the *AL* term of the Sonar equation, were significant at high concentrations.

In the Tylers Beach project on the James River, a prototype PLUMES was used to track the sediment plume associated with open-water disposal of dredged material (Thevenot, Prickett, and Kraus 1992). The dredged material was hydraulically dredged from the navigation channel and placed in a nearby relic channel. Regulatory agencies were concerned that sediment plumes associated with the disposal operation could adversely impact nearby shellfish resources. While tracking the movement of the sediment plumes, the PLUMES collected backscatter data that was used to estimate the TSS within the sediment plumes. In addition to the PLUMES data, in situ sampling included collection of water samples that were analyzed for TSS, conductivity, temperature, and density measurements, water-velocity measurements, and transmissometer readings.

Suspended-material concentration data and acoustic data from the prototype PLUMES were used to develop empirical correlations of backscatter strength to suspended-particle concentrations. A second correlation was conducted in the laboratory using sediment from the dredge site. While the correlations showed similar trends, significant discrepancies existed at lower sediment concentrations

(approximately 30 mg/L). Since the coefficients developed during the laboratory correlation were closer to the theoretical coefficients than the field-correlation coefficients, the decision was made to use the laboratory coefficients to process the data. The difference between the two correlations was likely due to unaccounted-for changes in the grain-size distribution in the sediment used in the field calibration. A comparison of the correlations over the range of suspended-sediment concentrations measured in the water samples shows differences in estimated sediment concentrations of up to 500 percent. The PLUMES was able to identify and track the movement of the sediment plumes, which did not appear to impact the sensitive shellfish areas.

Based on information derived from the prototype PLUMES tests, a second-generation PLUMES has been developed. This system was used to monitor the disposal of dredged material at a deepwater offshore disposal site near San Francisco, California, from hopper barges (Tubman, Brumley, and Puckette 1994). Regulatory agencies were concerned that dredged material suspended in the water column during the dumping of the hopper barges would migrate into a nearby marine sanctuary. Therefore, a monitoring program was established to track the sediment plumes. For this project, the PLUMES was mounted in a tow body that could be towed at various depths ranging from approximately 45 to 400 m. CTD and OBS sensors were also mounted on the towed body. In addition, a 75-kHz ADCP was used to monitor water velocities to a depth of 700 m and also provide qualitative information on the sediment plume created by disposal. A 200-kHz fathometer also proved extremely useful in identifying the sediment plume.

After the dredged material was released, the PLUMES was towed through the disposal area and the sediment plume identified. After the PLUMES passed through the sediment plume, a second ship attempted to collect water samples of the plume using bottle samplers. Because of the dynamic nature of the plume and the delay from the time when the plume was identified to the time when the water sampler could be deployed, attempts to sample the water containing the sediment plume were unsuccessful. The PLUMES system was able to successfully identify and track the sediment plumes for up to 6 hr after the disposal and as far away as 4 km.

Attempts to determine TSS using the sonar equation and the measured backscatter were unsuccessful for the San Francisco project (Tubman, Brumley, and Puckette 1994). Calibration coefficients for PLUMES necessary to solve the sonar equation could not be accurately determined through laboratory testing. The calibration problems could not be resolved, and therefore, calculation of suspended material from PLUMES-backscatter data could not be performed using the sonar equation.[1] Nonetheless, as demonstrated in field testing, the PLUMES is an effective tool for identifying and tracking suspended-sediment plumes. In many monitoring circumstances, this alone is sufficient to meet the monitoring requirements for a given project. If detailed information on the structure of the plume is required, empirical calibration of the system can be attempted through the extensive collection of water samples. However, even with the collection of numerous water samples for calibration, the rapid variations in time and space of the sediment concentrations in the plumes will make it difficult to develop an accurate correlation between the suspended-particle concentrations and the acoustic backscatter. Theoretical work using the sonar equation and

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[1]     Personal Communication, 1998, Michael W. Tubman, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

numerous backscatter data from field projects has shown that the acoustic performance of the Broadband ADCP™ is such that even in an ideal situation where there is a constant, known grain-size distribution, errors in the TSS concentration determined from the backscatter data can be as high as 100 percent.[1]

Another technique using the ADCP to monitor suspended sediments is the Sediview Method™ developed by Dredging Research Limited (DRL). The Sediview Method™ is similar to PLUMES in that it applies acoustic theory to measured backscatter data to estimate suspended sediment (Land and Bray 1998). The primary difference is that the Sediview Method™ can reduce the errors associated with the concentration-dependent acoustic-loss term by using an iterative approach in solving the sonar equation. This is important when high-sediment concentrations are encountered.

Like PLUMES, the Sediview Method™ collects data using a Broadband™ ADCP mounted from a vessel. The method can also use data from a Narrowband™ ADCP; however, the reported accuracy is significantly lower. The method requires an extensive calibration of the ADCP and collection of calibration data (water samples) during the collection of the acoustic-backscatter data. DRL recommends that calibration data consisting of at least one shallow water sample be collected as frequently as every 10 min during acoustic-data collection. In addition, more extensive calibration data must be collected throughout the entire water column at regular intervals during the collection of the acoustic data.

The Sediview Method™ includes a sophisticated data processing software package that directly incorporates the calibration data. The software employs an iterative approach to calculate the suspended-particle concentration from the acoustic backscatter. Limited published information is available on the data processing routine used by the Sediview Method™ and its results. Land and Bray (1998) claim that with "careful data collection and analysis, individual concentration estimates can be derived which are generally within 25% of the concentrations measured on contemporaneous water samples." A review of some of the data presented in the article indicates that this estimate of accuracy is based on a large number of samples taken in an area of relatively constant sediment concentration and grain-size distribution. However, no detailed statistical information on the accuracy of the system is provided. While the article does present data from a project measuring suspended-sediment concentrations in a plume generated by open-water disposal of dredged material, the accuracy of the method under such conditions is not discussed. Theoretically, estimating sediment concentrations in plumes is complicated by the rapid variation in sediment concentration and sediment size over short time periods and distances. As noted in the article, even with extensive sampling of the water for calibration, errors under such conditions are "unavoidable" (Land and Bray 1998).

Based on the limited information available, the Sediview Method™ appears to provide reasonable results under certain conditions provided extreme care is taken in applying the method. However, its ability to provide accurate measurements of TSS in sediment plumes has not been demonstrated.

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[1] Personal Communication, 1998, Michael W. Tubman, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

**Sidescan sonar:** Sidescan sonar is another acoustics technology that is being investigated as a possible tool to identify and track sediment plumes. A sidescan sonar emits a fan-shaped beam of acoustic energy into the water from an acoustic transducer. The beam is oriented vertically such that it "sees" a vertical slice of the water column with each pulse of acoustic energy. The transducer is typically mounted in a towfish body that is towed off the stern, bow, or side of a vessel such that the vessel does not interfere with the acoustic beam. The standard application of the sidescan is to look at variations in the acoustic-reflection characteristics of the bottom that may indicate changes in bottom type or the presence of an object. The range that the sidescan sonar "sees" is dependent on a variety of factors, but typically it is several hundred feet on either side of the towfish. By constantly emitting acoustic pules as the unit is towed and monitoring the return signal, the sidescan can generate an image of the seafloor showing variation in acoustic reflectance. Given the appropriate frequency of the transducer, the sidescan will also indicate the presence of suspended particles in the water column. Similar to the mapping of acoustic variation of the reflectance of the seafloor, a sidescan should be able to create an image of the variation in the backscatter caused by particles in the water column. In shallow waters, the data from the sidescan could be used to create a map of the approximate location of the plume relative to the sidescan towfish.

Applications of sidescan sonar to observe sediment plumes are limited. Suspended particles are typically seen as interference by operators attempting to image the bottom and are avoided. Sidescan has been used in a few instances to identify sewage outfall plumes; however, no studies using sidescan to monitor dredge plumes could be identified. Under the right conditions, sidescan could prove a useful tool in identifying the dimensions of sediment plumes (Personal Communications,[1] and Imaginex 1998). Since the systems can be towed, large areas can be covered making possible rapidly delineating the boundaries of a plume. Because of the nature of the acoustic beam generated by a sidescan, at best, a sidescan could provide only limited qualitative information about the suspended-sediment concentrations. Nonetheless, the ability to quickly map the dimensions of the plume would be extremely useful in plume monitoring. Researchers are currently exploring the feasibility of using of sidescan sonar technology to monitor sediment plumes.[2]

**Scanning sonar:** Another acoustic technology that may prove useful in the tracking of sediment plumes is the scanning sonar (Imaginex 1998). A scanning sonar is similar to the sidescan in that it has a fan-shaped beam oriented vertically; however, the scanning sonar beam is mechanically scanned 360 deg around a stationary point. The acoustic energy is reflected by objects in the beam, and the reflections are mapped on a screen. The output is very similar to that of a conventional radar system. Typically, these systems use a relatively high frequency (over 600 kHz) and have a range of up to 183 m (200 yd). Like other acoustic systems, suspended particles in the water column will backscatter the acoustic energy making it possible to identify the presence of suspended particles in the water column. One advantage to this type of technology is that the sonar can remain stationary as it is scanned making it possible to monitor the development of the sediment plume over time. Scanning sonar would only be able to provide qualitative information on concentrations of suspended particles in the plume. While no documented studies of the use of scanning sonar to

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[1]    Personal Communication, 1998, Jack Word, Pacific Northwest National Laboratory, Seattle, WA.

[2]    Personal Communication, 1998, John R. Proni, Atlantic Oceanographic and Meteorological Laboratory, Miami, FL.

monitor suspended-sediment plumes are available, the systems could prove an effective tool in determining the development and dimensions of dredge plumes.

## Remote Sensing

Several remote sensing techniques have been used to monitor suspended-sediment plumes. The most basic method is aerial photography, which under the right conditions, can provide very good information on the spatial extent of plumes in the uppermost part of the water column. Unfortunately, aerial photography is limited by daylight and weather. Additionally, it can be difficult to distinguish plumes in areas with high ambient suspended-sediment concentrations. Synoptic information provided by aerial photography can be useful in understanding the extent and development of dredge plumes.

Recent attempts to use aerial photography to track sediment plumes in the Cape Fear River near Wilmington, North Carolina, were unsuccessful because of the turbid waters in the vicinity of the dredge, which obscured the sediment plume.[1] A review of the literature found little published information on the use of aerial photography to identify and track sediment plumes.

Multispectral imagery is another remote sensing technique that has been used to track suspended-sediment plumes. To date research has focused on monitoring large-scale distributions of suspended-sediment plumes such as those associated with river discharges. Multispectral imagery is collected from satellites and aircraft using imaging sensors that concurrently collect energy from a number of spectral bands. The amount of energy measured in certain bands can be correlated with properties of the material reflecting the energy. Research has shown that it is possible to measure sediment discharges associated with rivers in a quantitative manner using multispectral imaging techniques (Gradie et al. 1995).

Multispectral techniques have limitations similar to those of aerial photography such as weather and daylight. However, multispectral imagery can in most cases distinguish sediment plumes in areas with high ambient turbidity. Even with limited application of multispectral techniques to monitoring of dredge-related sediment plumes, the technique may prove useful in identifying plume location and the extent of a plume.

## Dye Studies

Dye studies are used extensively to monitor plumes associated with sewage and stormwater outfalls. For this type of study, a fluorescing dye is injected into the outfall stream, and fluorometers are used to sample the concentrations of the dye at various locations in the receiving water body. Using such an approach allows monitoring how the plume from the outfall mixes with surrounding water (Battelle 1991).

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[1] Personal Communication, 1998, Phil Payonk, U.S. Army Engineer Engineer District, Wilmington, Wilmington, NC.

A similar approach has been used to monitor plumes of suspended sediment associated with dredging activities. In one such study (Marsh 1994) at the Port Edgar Marina in Scotland, a fluorescing particle tracer was used to track the dispersion of sediments associated with a water injection dredging project. A known volume of tracer was injected as sediment slurry directly into the water injector jet over a period of 30 min. Over the next 5 days, a series of water and sediment samples was collected at five locations near the marina. In addition, the fluorescent tracer particles in the water and the sediment layer were monitored using a real-time detector system. By monitoring the amount of tracer in the water column and in the sediment samples at various locations, researchers were able to estimate where the dredged material was redeposited. Redeposition rates estimated from the sediment-tracer concentrations corresponded well with measured rates. Measurements of the tracer concentrations 1 year after the original study proved useful in understanding the long-term movement of dredged material in the system.

Marsh (1994) demonstrated that particle-tracer techniques can be effective in monitoring the movement of sediment plumes associated with dredge activities. This technique appears to be particularly useful in studies concerned with deposition of dredged material in sensitive areas and the long-term movement of the sediment.

**SUMMARY:** As discussed above, a variety of instruments and techniques are available for the monitoring of dredge-generated sediment plumes. The success of any monitoring effort is critically dependent on matching tools and techniques to the goals of monitoring.

An effective monitoring program will first identify the locations and dimensions of the plume and then measure the appropriate parameters in the plume using in situ instrumentation. A standard fathometer that has been properly adjusted provides a cost-effective means of tracking the plume and delineating its dimensions. A PLUMES or an ADCP will provide more detailed information on the structure of the plume and will also provide detailed information on the currents affecting the plume. Until calibration problems encountered with the PLUMES are solved, using the PLUMES to measure TSS associated with a dredge plume is not recommended. Sidescan sonar and scanning sonar may be useful in monitoring the spatial extent of plumes; however, their effectiveness has not been demonstrated.

The collection of water quality data has been greatly simplified through advances in instrumentation. Instrument packages that can measure a variety of parameters and are suitable for deployment from small vessels are readily available. These packages can be used to profile the water column providing vertical coverage or can be towed slowly through the water column providing horizontal coverage. Under certain conditions and with the proper calibration, turbidity measurements can be used to estimate TSS. For verification of field measurements of TSS, water samples should be collected and analyzed in the laboratory. Instrumentation for measuring TSS in situ is commercially available; however, its accuracy has not been verified for monitoring of suspended-sediment plumes.

Spatial coverage of water quality measurements, both vertically and horizontally, can be greatly increased by mounting the instrumentation on a towed vertical profiling system. These systems have been used extensively to monitor sewage outfall plumes and have been shown to be very

effective at quickly collecting in situ water quality data over large areas. Even with little published information on their use to monitor sediment plumes, they should work well in this application.

Under appropriate conditions, aerial photography can provide useful information; however, because of limitations imposed on aerial photography by weather and daylight, aerial photography cannot provide the detailed information usually required for monitoring plumes. Other remote sensing techniques have similar limitations.

The use of particle-tracer dyes to study movement of plumes into sensitive areas has proven useful under certain circumstances. Particle tracers can be used to identify the presence of sediments resuspended by dredges in a particular area at concentrations comparable with background suspended-sediment concentrations. Such techniques would be useful in identifying sediment plumes in highly turbid areas or where long-term movement of dredged material is of interest.

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> Puckette, T. P. (1998) "Evaluation of dredged material plumes—Physical monitoring techniques," *DOER Technical Notes Collection* (TN DOER-E5), U.S. Army Engineer Reseach and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer*

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